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Sensory Substitution for Space Gloves and for Space Robots

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1. Abstract

~~This paper describes~~ sensory substitution systems for space applications. Physical sensors replace missing human receptors and feed information to the interpretive centers of a different sense. The brain is plastic enough so that, with training, the subject localizes the input as if it were received through the missing receptors.

Astronauts have difficulty feeling objects through space suit gloves because of their thickness and because of the 4.3 psi pressure difference. Miniature force sensors on the glove palm drive an electrotactile belt around the waist, thus augmenting the missing tactile sensation.

A proposed teleoperator system with telepresence for a space robot would incorporate teleproprioception and a force sensor/electrotactile belt sensory substitution system for teletouch.

2. Introduction

Sensory substitution is the provision to the brain of information that is usually in one sensory domain (e.g. visual information via the eyes and visual system) by means of the receptors, pathways and brain projection, integrative and interpretative areas of another sensory system (e.g. "visual" information through the skin and somatosensory system). Some examples include sign language for the deaf, Braille for the blind, and the various instrumentation approaches to providing sensory information to persons with specific sensory losses, such as tactile vision substitution systems for blind persons. This paper discusses sensory substitution and sensory augmentation in relation to space needs: augmented sensation for astronauts wearing the bulky gloves required for extravehicular activity and sensory information from space robot hands to the teleoperator.

3. Brain Plasticity as a Basis for Sensory Substitution

Among the most remarkable capabilities of the central nervous system (CNS) is the ability to compensate for losses caused by injuries. This capacity demonstrates that other brain areas are available to assume functions that were previously mediated by the lost neural tissue, or that the functions can be mediated by the remaining neural tissue. This property reflects the plasticity of the brain.

Plasticity is the attribute of the central nervous system in which enduring functional changes take place. It is one of the two fundamental properties of the nervous system; the other is its excitability, which relates to rapid changes leaving no trace in the nervous system.

Sensory information reaches the brain in the form of nerve impulses. There is no doubt that the temporal and spatial patterns of nerve impulses provide the basis of our sensory perception; the coding of information in the form of nerve impulse patterns is a fundamental concept in neurophysiology and psychology. For example, visual information is sent along the optic nerves in the form of patterns of nerve action potentials. The optical images, per se, reach no farther than the retinal receptors. The brain must interpret the nerve impulses as a visual image, after decoding the patterns of afferent impulses. The degree of plasticity available in these mechanisms will determine the functional limitations of sensory substitution systems. In sensory substitution, plasticity is probably the most critical factor of all the properties of the nervous system [1].

The transducer functions of a set of lost or unavailable receptors can be mediated by artificial receptors. For example, in tactile vision substitution systems the TV camera assumes the role. The optical display must be transduced to a form of stimulation that can be handled by the skin receptors, which then assume the functional role of relays. The plastic changes do not occur in the skin receptors or pathways, but in the CNS [1] [2].

4. Some Examples of Sensory Substitution

Two widely used sensory substitution methods are Braille and sign language. The first requires very little instrumentation and the latter, none at all; however, both accomplish the necessary sensory transformation: information usually in one (the lost) sensory domain is transduced to an appropriate display for another, intact sensory system.

(a) In Braille, letters are changed into raised dots; a code based on a 6-dot matrix was developed by Braille to enable blind persons to read letters with the fingertips. The critical factor is that this approach allows the blind person to achieve the same conceptual analysis and mental imagery from reading with the fingertips as the sighted person achieves by reading print.

(b) American sign language (ASL) is an incredibly ambitious and successful sensory substitution system. It translates information usually in the auditory (high frequency, low parallel input) domain into the visual (low frequency, high parallel input) domain. This is accomplished in real time as can be noted by watching a TV news program on which a signer is simultaneously translating into ASL ("translation" is the appropriate term: Bellugi and Klima [3] consider ASL to differ dramatically from English and other spoken languages, with distinct grammatical patterns and its own rules of syntax).

A number of sensory substitution systems requiring high technology have been or are being developed. These include tactile vision substitution, tactile auditory substitution, and tactile somatosensory substitution for insensate hands and feet.

(a) Tactile vision substitution--With a tactile vision substitution system developed in our laboratory, the spatial information gathered by a television camera under the subject's control is delivered to the skin through an array of vibratory stimulators or electrodes. With training, the blind subjects can identify and correctly locate in space complex forms, objects, figures, and faces. Perspective, parallax, size constancy, including looming and zooming and depth cues, are correctly utilized. The subjective localization of the information obtained through the television camera is not on the skin; it is accurately located in the three-dimensional space in front of the camera, whether the skin stimulation matrix is placed on the back, on the abdomen, on the thigh, or changed from one of these body locations to another.

The instrumentation and the research results have been widely reported [1] [4] [5] [6] [7]. A curriculum has been developed to teach congenitally blind children visual spatial concepts, and is being field tested in the United States and Spain.

(b) Tactile auditory substitution--A comparable tactile auditory substitution system has been developed and is now a commercial product (Tacticon). Auditory signals picked up by a microphone are divided into frequency bands and each of these drives one of 16 electrodes on an electrotactile belt worn around the waist, with low tones at one end and high tones at the other [8].

(c) Tactile somatosensory substitution--Some years ago, in collaboration with C. C. Collins, the feasibility of providing tactile information to leprosy patients with insensate hands was explored. A single strain gage was located in each fingertip of a glove worn on one hand, and the information was delivered to the skin of the forehead (where sensation was intact) through five electrotactile stimulators. Within a few hours of training, it was possible to locate the sensation on the fingertips, and it was possible to identify various textures [5]. As with the tactile vision substitution system, correct subjective localization (in this case to the fingertips) required active control of movement by the subject.

The success with the leprosy patient study led to the exploration of other applications. Funded studies are now underway to explore the application of this approach to patients with insensate feet due to diabetes, and to space suit gloves and space robots.

5. Space Suit Glove Requirements

The need for human protection against the space environment began in the Gemini Program of the 1960s. Since then, manned space flight has progressed through the Apollo and Skylab eras, is currently in the Shuttle era, and planning for the Space Station era. Throughout these eras, the space suit glove has evolved into a complicated piece of the extravehicular mobility unit (EMU) and has improved greatly in areas of mobility and dexterity. The EMU is essentially an anthropomorphic enclosure for which the human can operate in the space environment and is shown in Fig. 1 for the Space shuttle era. Extravehicular activity (EVA) has become a much-needed resource in space operations and problems with human performance (in addition to those of a lack of EVA manhours available) are still apparent. In the Space Station era, more than 2000 EVA manhours may be needed to perform construction, assembly, servicing and maintenance activities. Many tasks for the astronauts have been structured around the existing glove capabilities; what activities and tasks could be accomplished with an optimal space suit glove? A perceived optimal glove is shown in Fig. 2.

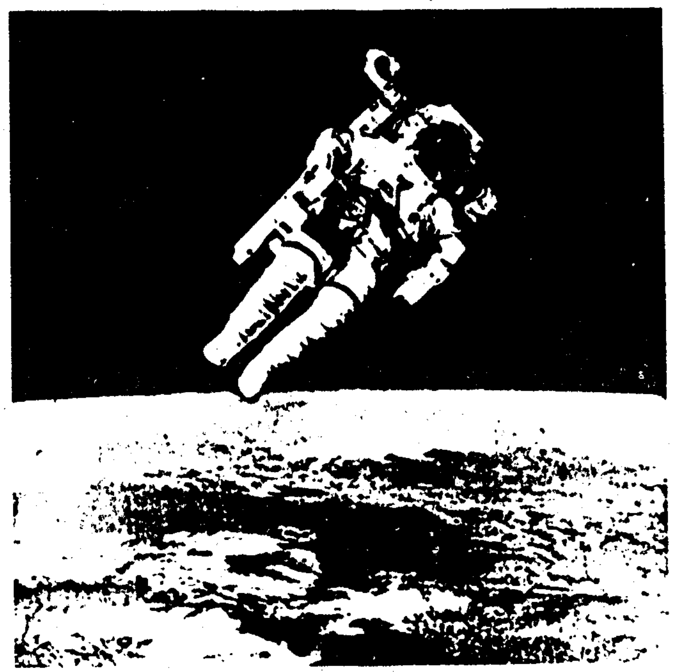

Fig. 1 The extravehicular mobility unit (EMU) is an anthropomorphic enclosure that assists human mobility and dexterity in space.

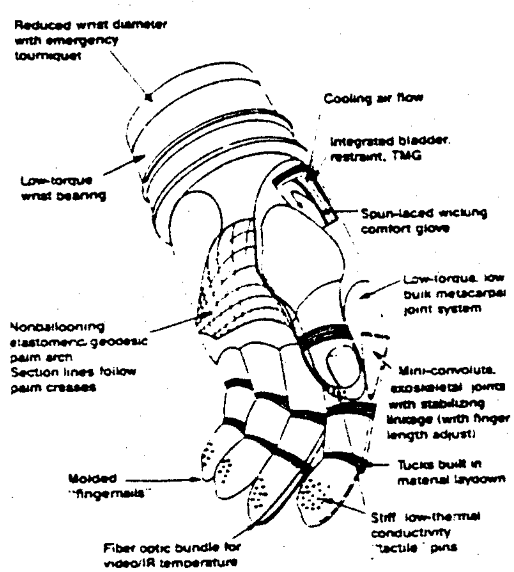

Fig. 2 Optimized EVA Glove.

For the future Space Station, 15 generic EVA activities have been defined as references for EVA system design. These include [9]:

1. Alignment of transmitter and receiver elements
2. Deployment/retraction of solar arrays
3. Truss structure construction
4. Satellite servicing
5. Large module manipulation
6. Small module manipulation
7. Large mirror construction
8. Consumable recharge via module transport
9. Orbit launch operations
10. Satellite operations
11. Space Station radiator construction (from STS)
12. Space Station radiator construction (from Space Station)
13. STS-supported large module manipulation
14. STS-supported truss construction/deployment
15. EVA rescue.

Many of these contain tasks and activities which require fine control and manipulation. Installation of hardware including assembly, replacement of orbital replacement units (ORUs) contingency maintenance and repair, transfer of equipment in and out of pressurized modules, routine support servicing and handling of fluids, equipment stowage, and platform support represent a few of these tasks. The EVA gloves provide the major and sometimes only interface between the astronaut and the work being performed and thus must provide a balance of mobility, tactility comfort, and protection from the workplace hazards.

6. Space Suit Glove Problems

A problem encountered by astronauts during extravehicular activity is that they have trouble feeling objects through their space suit gloves. The glove is made of several layers of plastic and fabric. The plastic prevents air leakage. The cloth provides strength so the plastic will not burst. The cloth also provides thermal insulation and protection from micrometeoroids. It is difficult to feel objects through these layers or through the thick silicone rubber fingertips.

Another even larger problem is that of the astronaut fatigue from work required to move the glove from its neutral position due to the difference between the space suit and space environment pressures. The pressure of the space suit for the Shuttle is 4.3 psi and planned at 8.3 psi for the Space Station. In addition, more radiation and micrometeoroid/debris protection will be required. All of these factors inhibit the design of a flexible and dexterous glove with good sensory capabilities. Answers to both of these problems and many more being addressed by NASA would greatly enhance the performance of the astronaut on EVA. Current training practices have allowed substitution of perception for the lack of tactility. Enhancement of the tactile sensory perception may reduce the fatigue problem, increase the EVA capability to finer motor control, allow the enhancement of the glove design without detriment to the tactility, reduce the astronaut reliance on visual feedback, and thus reduce training time to learn certain tasks. The pressure within the glove causes two major effects. The first is stiffness of the glove itself reducing freedom of position. This restricts the movement of the glove without a great deal of work. Over a large period of time (such as the standard EVA of six hours), the hand is subject to extreme fatigue. Some of this fatigue is due to overgripping to ensure contact. Providing the tactile feedback will give the sense of contact and reduce overgripping thereby reducing the fatigue.

Second, the present air pressure difference of 4.3 psi causes the glove to balloon out. This reduces the tactility between handholds and tools. The resulting tangential forces on the surface of the glove make it difficult to perceive normal forces through the glove. An analogous situation is trying to feel a pebble through a bicycle tire. If the tire is flat, it is easy to feel the pebble through it. If the tire is pressurized, it is very difficult. The proposed space suits would have a 8.3 psi pressure difference, which would make the problem much worse.

The result of this problem is that the astronaut cannot feel when a tool is starting to slip. He overcompensates for this by applying a higher than required force to ensure adequate grasp. His muscles tire quickly and he becomes fatigued much sooner. Force is again used to compensate for this to assure contact. To reduce this ballooning effect, which also reduces the astronaut's capability to grasp an object, NASA has tried hard palms and other palm restraints. The restraint is necessary to enable adequate bending of the metacarpal joint. Solutions to this problem have met with mixed success during the astronaut evaluations. Tactile sensors on the restraint may make such a design feasible in terms of tactility and interfacing with tools, handholds, and other objects.

As Dr. George Nelson reports of his Solar Max Repair activity in space, glove limitations are minimal for gross motor control but are almost inhibitive for fine motor control. His projection indicates that 20% dexterity is lost when handling objects of one inch in diameter and 50% for objects of less than one inch. For objects of millimeter size, the glove permits almost no fine motor control, due to lack of flexibility in conducting more detailed tasks. Dr. Nelson recommends increased tactility especially in the areas of the fingertips and the full length of the index finger and thumb.

Loss of tactility in the space suit glove has been estimated to cause more detriment to EVA performance than is recognized by the crewmembers. Much of the loss of tactility is compensated by visual perception of the task during the many hundreds of hours of training. Providing tactile feedback would relieve the need for such a substitute and possibly reduce the amount of training to perform a specific task.

NASA has looked at mainly passive means in which to increase the tactile feedback to the astronaut including movable pins, enhanced fingertip tactile pads, glove/hand adhesion, and removable fingertips to expose a less bulky, less protected finger. One concept is shown in Fig. 3. Other means such as sensory substitution have also been recommended for feeding other senses such as vision or hearing. The concept discussed here is active tactile sensory perception inducing a simple relocation of the pressure to the abdomen or forearm. Thus the other senses of sight and sound are not overburdened.

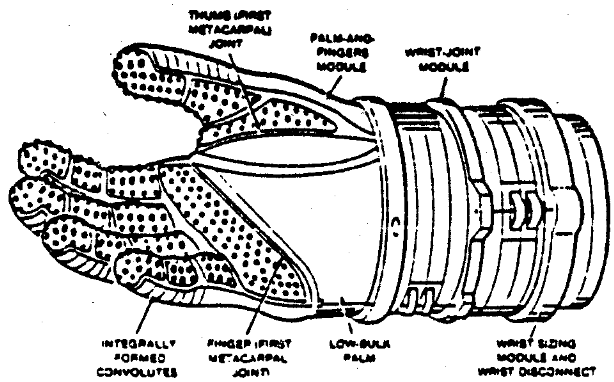

Fig. 3 Thermally insulated glove contains short, closely-spaced elastomeric pins that insulate without impairing flexibility.

7. Space Suit Glove Sensory Substitution

Based on sensory substitution mentioned above and reported in detail elsewhere, we proposed a study of tactile sensory substitution for space suit gloves to increase the performance of extravehicular astronauts by increasing tactile sensation. The working hypothesis is that sensory information gathered by the active control of hand movement would be subjectively located in the hand, even though the information arrives at the body at another location (e.g., skin of the abdomen or arm).

We have built a sensory substitution system where the force sensors are on the outside of the glove and are exposed directly to the grasped object. They are located at the points of maximal information, such as the inside of the thumb and first two fingers. We determined these locations by observing wear patterns of used space suit gloves and by grasping various tools using space suit gloves.

A problem in attaching the force transducers is that as the hand is closed, deep wrinkles form on the outer fabric layer of the glove. A small transducer attached to the fabric surface might shift into the pocket of a wrinkle and not detect the surface force at all. To overcome this problem we placed 0.8-mm thick 11-mm diameter metal disks at each location. These had four 1-mm holes at 4 peripheral locations. We used nylon fishline to sew the disks loosely to the fabric. This permitted wrinkles to form but kept the disks parallel to the surface.

Constraints on the selection of a force transducer are that it should be small, have low power consumption, have a wide temperature range, and be rugged. Possible transducer types include strain gages, inductance transducers, optical transducers, piezoelectric transducers, conductive elastomers, time-of-flight transducers, and capacitive transducers. The smallest commercial transducer we found is the Model 105 pressure transducer: 80 psi, 350 ohm from Precision Measurement Company, Box 7676, Ann Arbor, MI 48107. It is 0.28 mm thick and 2.6 mm in diameter. We enclosed the 3 fragile wires from the 1-arm metal strain gage transducer in heat shrink tubing. Using Dow Corning No. 891 Medical Adhesive Silicone Type A, we glued the transducer to the disk and formed a rounded surface of adhesive over the top of the transducer. Thus the rubbery adhesive transmitted forces to the diaphragm of the pressure transducer. We routed wires under the outer fabric layer from the palm to the wrist connector.

We constructed our own electronics to drive a commercial electrotactile system. Because the transducer has only one strain gage element, we added three resistors to complete a Wheatstone bridge. An operational amplifier amplified the small signal from the bridge to a large signal suitable for driving the electrotactile system. Potentiometers to adjust offset and gain were required.

We purchased a Tacticon 1600 electrotactile sensory aid for the deaf. It has a microphone input, divides speech into frequency bands, and delivers electrical stimuli to the skin through 16 gold-plated 5-mm diameter electrodes. A belt around the waist positions the electrodes over the abdomen and receives power from a battery pack and electronics located in a box clipped to the user's normal belt. We removed the speech system and fed the drivers from our amplifiers.

The system worked well in that each user could establish cause and effect between pressure on a specific transducer and electrical stimulation at a particular electrode. Unfortunately our original estimate that 80 psi transducers would be satisfactory was wrong. Firm grasp of tools, such as screwdriver handles overstressed the transducer diaphragms beyond the yield strength, resulting in permanent damage. Thus we are restricted to light pressures. We have ordered 1000 psi transducers and will test those under more rigorous conditions.

We expect that a period of learning will be required for optimal interpretation of this alternative sensory system. We plan an evaluation by skilled astronauts performing typical tasks in a pressurized glove box after an 8-hour learning session.

8. Space Robots

NASA has proposed a space robot that would perform tasks in space under the control of an astronaut in a spacecraft or by ground controllers. The astronaut would control the robot in a master-slave relationship called teleoperation. The astronaut would place his hands and arms in controlling gloves and mechanical arms. When the astronaut would move, the robot would exactly follow him.

Figure 4 shows an additional system, called telepresence, which would provide sensation to the astronaut. When the robot's hand would close on an object, the astronaut's hand inside the controlling glove would feel the same mechanical resistance through proprioception. This teleproprioception [10] would be accomplished by actuators in the astronaut's controlling glove which would be slaved to the actuator in the robot's hand and increase the force that resists controlling glove closure. The astronaut would receive direct position feedback of robot joint angles from his own joint receptors. He would receive direct force feedback of robot forces from his own muscle and tendon receptors. Teleproprioception would provide feedback about the large forces resulting from firm grasp, but not the small forces associated with slip. Figure 5 shows a one-degree-of-freedom system that would provide both teleoperation and teleproprioception.

None of the telerobotic systems described above include teletouch [10]. The human palmar skin contains a variety of mechanoreceptors to sense light touch and nociceptors to sense the pain that results from high pressures. Thus when the robot senses objects at different locations within the palm, this information should be sensed and transmitted to the astronaut. If an object is slipping from the robot's grasp, the astronaut should receive the same sensations as if the object were slipping from his grasp.

Thus the robot's palm should be covered with many force sensors. These should detect small forces necessary to detect slip. They should be capable of withstanding large overloads as when the robot grasps tools firmly. Most transducers have a deformable element such as a spring. Most transducers are designed to operate to an appreciable fraction of their yield strength to give a large output and thus they overload easily. What is needed is an element that deforms easily to produce a sensitive range, but then hits a mechanical stop to be able to withstand high forces during overload. It will be a challenge to develop such transducers in miniature form.

If the astronaut grasped a sharp pointed object, his skin would indent. The ideal teletouch system would also indent his skin. An array of solenoids or air bladders might accomplish this goal, but it would be difficult to miniaturize an array to fit in the controlling glove. If such a system were impossible to develop, the next best solution would be a sensory substitution system. Information from touch sensors on the robot palm would drive stimulators on the palm. These might be vibrotactile arrays located in similar palmar areas within the astronaut's controlling glove. Electrotactile stimulators on the palm are not practical because the thick skin results in painful stimulation. But electrotactile stimulators on a belt around the waist are practical and could be used in a successful system.

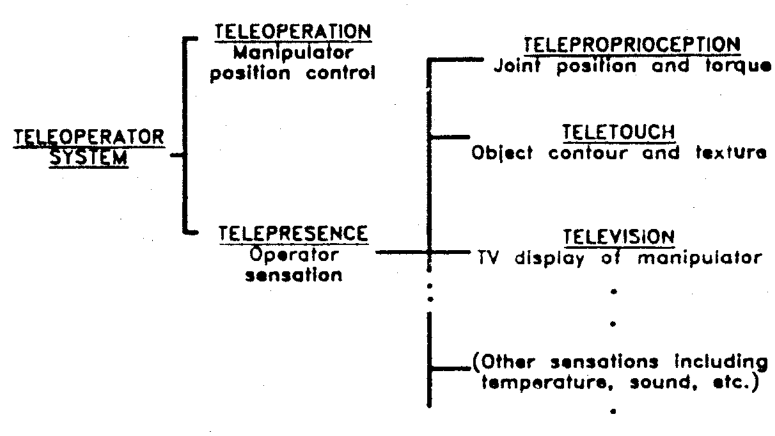

Fig. 4 Different elements of a teleoperator system showing the separation of the proprioceptive and tactile sensory feedback.

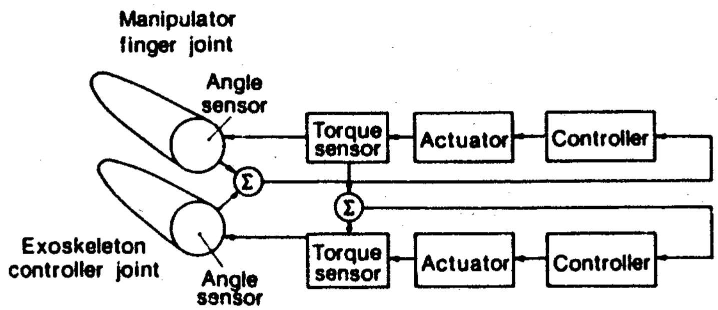

Fig. 5 Block diagram of a one degree-of-freedom force-reflecting control scheme providing teleoperation and teleproprioception.

For a robot to be useful in space, it should be anthropomorphic. Its hand should resemble our hand, so that it can perform the same tasks the astronaut can. Also if the robot fails, an astronaut must perform the robot's tasks. Several groups have developed anthropomorphic-like hands. None has developed teleproprioception for the hand. None has developed teletouch for the hand. It will be a challenge to implement telepresence in the limited space available within the normal boundaries of a hand.

9. Acknowledgements

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